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Coordinate Space Distributions of Antiquark Flavor Asymmetries in the Proton *)

Ernest M. Henley[a,b], Thorsten Renk[c], and Wolfram Weise[c]

[a] *Department of Physics, University of Washington, Seattle, WA 98195, USA*

[b] *Institute for Nuclear Theory, University of Washington, Seattle, WA 98195, USA*

[c] *Physik Department, Technische Universität München, D85747 Garching, GERMANY*

Abstract

We examine the space-time properties of the distributions of $(\bar{d}-\bar{u})$ and $\bar{d}/\bar{u}$ in the proton. The difference of the antiquark distributions shows the expected peak at the approximate pion Compton wavelength and is supportive of the thesis that the meson cloud of the nucleon is at the origin of the asymmetry of $(\bar{d}-\bar{u})$, with the pion cloud playing a dominant role.

The partonic distribution functions of the proton, particularly the flavor dependence of the antiquark distributions, remain of considerable interest. Experimentally, the NMC measurement of the integral of $(\bar{d}-\bar{u})$ [1], and the more recent measurements of the ratio $\bar{d}/\bar{u}$ by means of the Drell-Yan process [2, 3] provide evidence for the excess of $\bar{d}$ over $\bar{u}$ in the proton. Similar results for $(\bar{d}-\bar{u})$ were obtained by HERMES [4]. One of the simplest (physically "anschaulich") explanations for the excess is based on the meson cloud model and the Sullivan process. This model can explain the momentum fraction (Bjorken x-dependence) of the $(\bar{d}-\bar{u})$ distribution (for reviews, see [5]). Pions play the leading role in this context, while the detailed description of the ratio $\bar{d}/\bar{u}$ may also require correlated $q\bar{q}$ pairs of heavier mass[3, 6, 7].

In this Letter we do not wish to dwell on the differences between theoretical models and experiment, but examine the spacetime properties of the flavor distribution asymmetries in order to see whether they offer any clues as to their origin. In order to obtain the distribution functions in coordinate space, we follow Piller et al. [8] and Vänttinen et al. [9]. We work with light-cone variables and introduce the dimensionless coordinate spacetime variable $z = y \cdot P$, where P is the momentum of the nucleon. The light cone distance is $y^+ \equiv t + y_3 = 2z/M$, with M the nucleon mass. The dimensionless space

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variable z is conjugate to Bjorken x and $z \simeq 5$ corresponds to $y^+ \simeq 2$ fm or a longitudinal distance of approximately 1 fm.

In the first instance we use empirical distribution functions and differences thereof. In accordance with the charge conjugation properties of momentum space quark distributions we find the coordinate space distribution of the sea quarks as

$$Q_{sea}(z, Q^2) = \int_0^1 dx \left[q_{sea}(x, Q^2) + \bar{q}(x, Q^2)\right] \sin(zx) \tag{1}$$

Decomposing this result into the contributions from quarks and antiquarks of different flavours we arrive at an expression for the asymmerty in coordiante space:

$$(\bar{D} - \bar{U})(z, Q^2) = \int_0^1 dx \left[\bar{d}(x, Q^2) - \bar{u}(x, Q^2)\right] \sin(zx) \tag{2}$$

The distribution functions $\bar{d}(x), \bar{u}(x)$ have been obtained from various deep inelastic electron scattering scattering and Drell-Yan experiments by CTEQ5 and other groups [10, 11, 12]. In Fig.1 we show $(\bar{d}-\bar{u})$ and $(\bar{D}-\bar{U})$ obtained from Eq.(2) and the CTEQ5, the MRST and the GRV analysis. We observe that all three parameterizations agree fairly well between each other except for small values of x or large z. Therefore we will mainly use the results from CTEQ5 in the following for comparison to the pion cloud model.

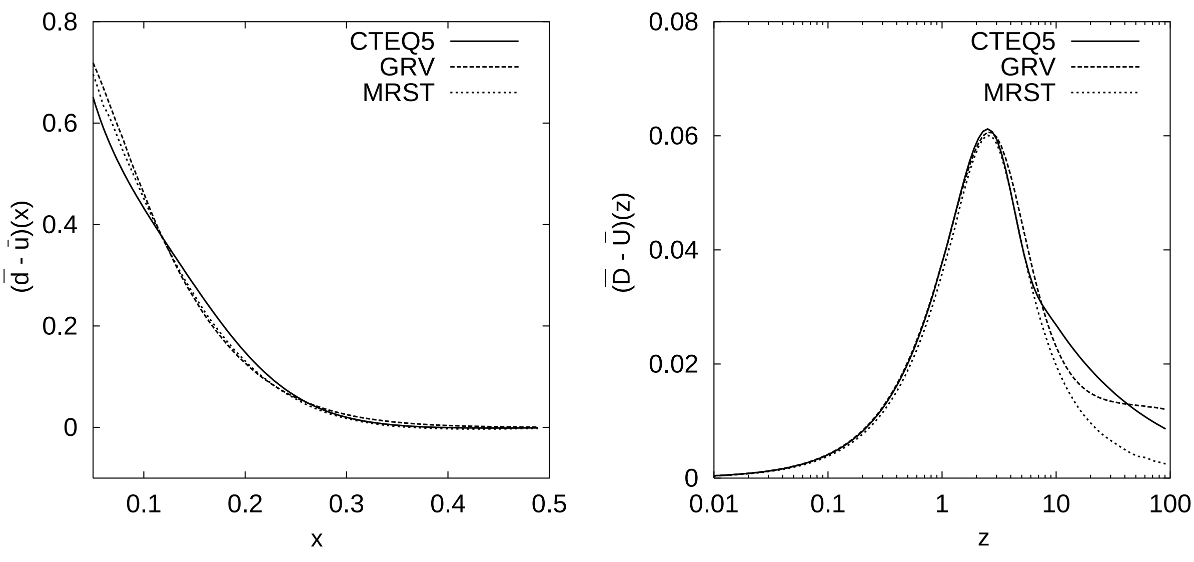

Figure 1: Momentum space and coordinate space distribution of the $\bar{d}-\bar{u}$ asymmetry in the proton at $Q^2 = 4$ GeV^2, based on the parameterizations [10, 11, 12].

Investigating the coordinate space distribution, we see that for $Q^2 = 4\,\text{GeV}^2$ the peak of $(\bar{D} - \bar{U})$ occurs at $z \simeq 3$ or at $y^+ \simeq 1.2$ fm. The half-width of the peak extends

from $z \simeq 1-10$ or $y^+ \simeq 0.4-4$ fm. This is a region where the pion and perhaps more massive $q\bar{q}$ states [7] contribute. We recall that at 3-4 fm, the valence quark distribution has fallen to less than 25% of its peak value.

In Fig. 2 we show the ratio $R(z) = \bar{D}(z)/\bar{U}(z)$ as a function of z. Here the small z region is expected to be constant because $\bar{q}(x) \simeq 0$ for $x \geq 0.35$, so that for $z \leq 1$, Eq. (1) becomes

$$\bar{Q}(z) \simeq z \int_0^1 \bar{q}(x)\, x\, dx = constant \cdot z\ . \tag{3}$$

It follows that the ratio $R(z)$ is a constant for $z \lesssim 1$. Most of the "action" takes place where the derivative of $R(z)$ differs appreciably from zero, which again occurs for $z \simeq 2-10$, corresponding to distance scales comparable to the size of the nucleon. We interpret these features as being supportive of a meson cloud as the primary cause for the excess of $\bar{d}(x)$ over $\bar{u}(x)$ in the proton.

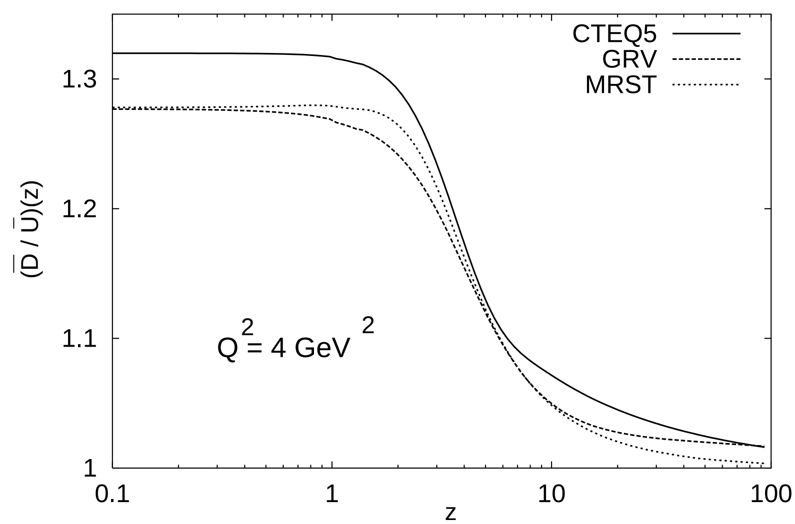

Figure 2: The Ratio $R(z) = \bar{D}(z)/\bar{U}(z)$ in coordinate space for different parametrizations.

In order to make a detailed comparison with the meson cloud model and Sullivan process, we have used it in its simplest form with only pions and no Δ and have concentrated on $(\bar{d}-\bar{u})$ because the detailed description of the ratio $\bar{d}/\bar{u}$ also requires the perturbative contribution from gluon splitting which is expected to be symmetric in $\bar{d}$ and $\bar{u}$.

We provide the usual formulae [5] for the effects of the meson cloud (and Sullivan process). The wave function of the proton is written in terms of Fock states with and without mesons:

$$| p\rangle = \sqrt{Z} \mid p\rangle_{\rm bare} + \sum_{MB} \int dy\, d^2k_\perp\, \phi_{BM}(y, k_\perp^2) \mid B(y, \vec{k}_\perp) M(1-y, -\vec{k}_\perp)\rangle \; . \tag{4}$$

Here $\sqrt{Z}$ is a wavefunction renormalization constant, $\phi_{BM}(y, k_\perp^2)$ is the probability amplitude for finding a physical nucleon in a state consisting of a baryon, B, with longitudinal momentum fraction y, and a meson, M, of momentum fraction $(1-y)$ and squared transverse relative momentum $k_\perp^2$.

The quark distribution function $q(x)$ of a proton is given by

$$q(x) = q^{\rm bare}(x) + \delta q(x) \; , \tag{5}$$

with

$$\delta q(x) = \sum_{MB} \left(\int_x^1 f_{MB}(y) q_M \left(\frac{x}{y}\right) \frac{dy}{y} \; + \int_x^1 f_{BM}(y) q_B \left(\frac{x}{y}\right) \frac{dy}{y} \right) , \tag{6}$$

where q_M and q_B are the quark distributions in the meson and baryon,

$$f_{MB}(y) = f_{BM}(1-y) \; , \tag{7}$$

$$f_{BM}(y) = \int_0^\infty \mid \phi_{BM}(y, k_\perp^2) \mid^2 \; d^2k_\perp \; . \tag{8}$$

The meson–baryon vertex function ϕ_{BM} includes a cutoff factor

$$G_M(t, u) = \exp \frac{t - m_M^2}{2\Lambda_M^2} \exp \frac{u - m_B^2}{2\Lambda_M^2} \; , \tag{9}$$

where Λ_M is a cut-off parameter for pions and t and u are the usual Mandelstam kinematical variables, expressed in terms of $\vec{k}_\perp$ and y. Such a form is required to respect the identity (7)[5, 13].

The cut-off required in the model is taken from ref. [5], but it is also varied to study its effect. We found that the cutoff basically regulates the overall normalization of the result and used the value which leads to the best fit ($\Lambda_M = 0.85$ GeV).

The expressions for the splitting functions $f_{MB}(y)$ are those given by [5] as derived in Ref. [14]. We include only the pion; then the renormalization constant of the "bare" quark is $Z = 1 - 3n_\pi$ where n_π is the probability to find a neutral pion in the cloud.

We need the valence quark distributions in the pion [15], $q_M(x)$, which is given at $Q^2 = 4$ GeV ^{2} as

$$xq_M(x) = 0.99x^{0.61}(1-x)^{1.02}, \tag{10}$$

and its Q^2 evolution. At this point, a problem arises caused by the fact that the parton distributions of the pion were extracted from πN scattering assuming that the nucleon ones are known. Since in our approach the nucleon also has an admixture of the pion cloud, the extraction of the pionic parton distributions is not fully consistent within this framework and therefore we do not expect a perfect agreement with data in the end. We do not need the bare nucleon sea since it averages out in the difference $(\bar{d}-\bar{u})$, which is our main interest.

The results of our calculations for $\bar{d}(x)-\bar{u}(x)$, using a cutoff $\Lambda_M = 0.85$ GeV, are compared to CTEQ5 in Fig. 3.

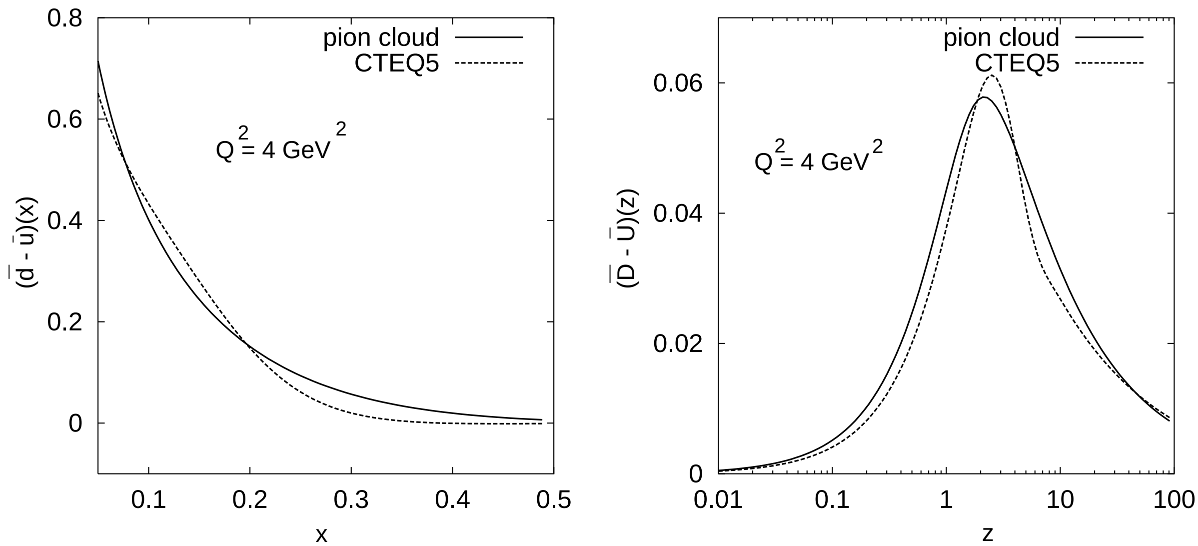

Figure 3: The asymmetry $\bar{d}-\bar{u}$ in momentum space and $\bar{D}-\bar{U}$ in coordinate space in the pion cloud model calculations and in the CTEQ5 parametrization.

Also shown in this figure is the space coordinate transform $\bar{D}-\bar{U}$. The peak occurs for a somewhat lower z than obtained by CTEQ5, however the overall agreement is obvious.

Finally, Fig. 4 shows the Q^2 evolution of the results obtained within the pion cloud model and in the CTEQ5 asymmetry. The Q^2 dependence of the pion cloud asymmetry evidently has the same qualitative feature as in the Q^2 evolution of the CTEQ5 results, namely a shift of the peak to higher z and a decrease of the maximum peak value with increasing Q^2.

We summarize and conclude with the following observations. The spacetime coordinate representation of sea quark distributions offers detailed insights, additional to their momentum space form, into the flavour asymmetry $\bar{d}-\bar{u}$ of antiquarks. In the Q^2 range between 5 and 25 GeV^2, this asymmetry is maximal in coordinate space at length scales (1.2 – 1.6) fm characteristic of the pion cloud of the nucleon. These features are evident in the empirical asymmetry distributions, and they are well undersood in the pion cloud

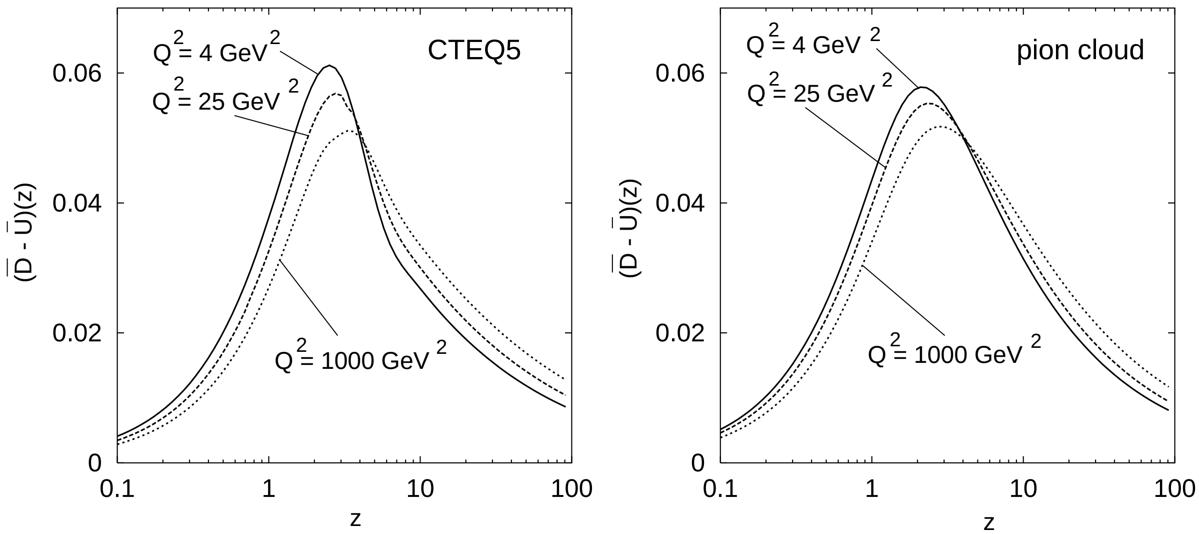

Figure 4: Q^2-evolution of $\bar{D} - \bar{U}$ in the pion cloud model and in the CTEQ5 parameterization.

model. Additional contributions of heavier masses may assist in reproducing the detailed behaviour of the $\bar{d}/\bar{u}$ ratio.

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